ANALYSIS OF HIGH BAY HANGAR FACILITIES FOR DETECTOR SENSITIVITY AND PLACEMENT

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ABSTRACT

This study was conducted to investigate the response of various fire detectors and automatic sprinklers in high bay aircraft hangars. Laboratory and full-scale experiments as well as computer modeling were conducted to better understand the movement of heat and products of combustion in high bay spaces. Temperature distribution across the ceiling was measured along with the response of various types of fire protection devices as a function of fire size, fuel type, and ventilation conditions. Key findings are presented relating to detector spacing, threshold fire sizes, sprinkler type and temperature ratings, burn rates, heat release rates, and the effect of draft curtains.

INTRODUCTION

Building and fire codes in the United States offer little or no guidance in the design of fire protection systems in high bay spaces due to the lack of scientific data. Such high bay spaces include aircraft hangars, hotel atria, warehouses, etc. Existing computer fire models do not provide reliable predictions for the activation of detectors and automatic sprinklers in buildings with high ceiling heights[1]. Most of the existing models[2] were developed based on correlations from fire tests conducted with ceiling heights up to 9.1 m. Also, only limited experimental data exist on the response of sprinklers and detectors at ceiling heights over 9.1 m. For these reasons, design engineers and code officials are often forced to make educated guesses as to the appropriate type of fire protection devices for high bay structures. Consequently, many existing high bay structures have installed fire protection systems which may prove ineffective in the event of a fire. Furthermore, the higher a building's ceiling height, the more uncertainty exists concerning the effectiveness of conventional fire protection. Due to this uncertainty, fire protection systems are less likely to be installed in these spaces.

The Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST) has been conducting research into the prediction of smoke detector response in high bay spaces since 1991. The focus of this paper is on th- full-scale experiments conducted by

NIST and the Naval Facilities Engineering Command (NAVFAC). These experiments were designed to assist the Navy in reevaluating its criteria for the protection of high bay aircraft hangars. Previous studies conducted by NIST in hangars with 15 m and 30.4 m ceiling heights used isopropyl alcohol, involved only one fire size, and were conducted with the hangar doors only in the closed position[3]. In this study, experiments were conducted with numerous fire sizes, aviation fuels, and hangar doors in both the open and closed positions. Also participating in these experiments were five private industry sponsors representing the U.S. fire alarm and automatic sprinkler industries, as well as representatives from each branch of the U.S. Department of Defense, and representatives from select technical committees of the National Fire Protection Association (NFPA).

SCOPE

The current national fire code requirements in the United States include the use of deluge-type sprinklers in military aircraft hangars[4]. However, those requirements are designed only to protect the building, not the aircraft. In addition, numerous false activations of overhead deluge sprinkler systems have resulted in significant damage to open-cockpit aircraft on the hangar floor. Current U.S. military criteria has shifted to the use of closed-head sprinkler systems and a total fire protection design aimed at providing protection for adjacent aircraft as well as the building[5]. This project was designed to provide scientific data on the response of fire detection and fire suppression devices in high bay aircraft hangars. Appropriate criteria may then be established for fire protection in these spaces.

This study consisted of 33 full-scale fire experiments in two Navy aircraft hangars, one located in a warm climate (average ambient temperature over experimental series 29 °C) and one in a cold climate (average ambient temperature over experimental series 12 ° C). The warm-climate experiments were conducted in a 15 m high hangar with a nominally flat roof. The cold-climate experiments were conducted in a 22 m high hangar with a barrel-shaped roof.

The 15 m tall hangar did not have draft curtains. This allowed for the fabrication and installation of a temporary draft curtain. Key experiments conducted in this facility were repeated with and without the draft curtain. This permitted data to be collected on the effects of draft curtains with respect to smoke and heat build-up in the draft-curtained area, smoke movement in the building, and response characteristics of the various fire protection devices.

Each of the two test hangars was first modeled using a computational fluid dynamics model, Harwell FLOW3D[6], to help design the instrumentation plan. Laboratory-scale experiments were conducted at NIST to measure the burning rate of JP-4, JP-5 and JP-8 to aid in the design of the full-scale experimental fires. Table 1 is a log of all the full-scale experiments. The fire sizes were designed based on ceiling height and calculated detector and sprinkler response. In each hangar, one range of fire sizes was designed to determine the threshold response levels of the flame and smoke detectors (i.e., detector fires). A second range of fire sizes was designed to determine the threshold response levels of the heat detectors and automatic sprinklers (i.e., sprinkler fires). In the 15 m hangar, the detector fire sizes ranged from 0.3 m x 0.3 m pans to 0.9 m x 0.9 m pans, and the sprinkler fire sizes ranged from 1.5 m diameter pans to 2.5 m diameter pans. In the 22 m hangar, the detector fire sizes ranged from 0.3 m x 0.3 m pans to 1.2 m x 1.2 m pans, and the sprinkler fire sizes ranged from 2.0 m diameter pans to 4.6 m x 4.6 m pans.

Previous fire detection and suppression techniques for military hangars were based on JP-4 fuel which has a flash point of approximately -12 °C. U. S. military aircraft are now fueled primarily with JP-5 and JP-8 whose flash points are approximately 63 °C and 46 °C respectively. The experiments were conducted using both JP-5 and JP-8 fuels. The following parameters were investigated:

- Effectiveness of spot-type and line-type heat detectors for high bay hangars
- Spacing of spot-type detectors in high bay hangars
- Approximate minimum fire size threshold for each detector type
- Effect of fuel type on the response of each type of fire detector
- Response distance thresholds of optical detectors to various fire sizes and fuel types
- Effects of temperature, stratification and wind on detector performance
- Overall performance of heat, smoke and projected beam detectors in high bay hangars
- Response of closed-head sprinklers systems versus deluge sprinklers
- Approximate minimum fire size for sprinkler activation for various sprinkler heads
- Effects of draft curtains on sprinkler and detector response
- Effects of an open-door fire on detector and sprinkler response

EXPERIMENTAL FACILITIES

In the laboratory experiments conducted at NIST, two major apparatuses were used to measure the burning rate of JP-4, JP-5 and JP-8 aviation fuels. The smallest fires, 0.085 m, were conducted in a cone calorimeter [7]. The 1.0 m and 1.2 m diameter fires were conducted in a large calorimeter, capable of handling 1.2 m diameter pool fires.

The first set of full-scale experiments was conducted in a 15 m high aircraft hangar at the U.S. Naval Air Station in Barbers Point, Hawaii. The second set of full-scale experiments was conducted in a 22 m high aircraft hangar at the U.S. Naval Air Station in Keflavik, Iceland.

A plan view of the hangar bay and fire area for the 15 m hangar is shown in figure 1. The hangar bay dimensions are approximately 97.8 m by 73.8 m. The east and west walls are comprised of concrete masonry construction with numerous unprotected window and door openings into the hangar bay. These walls are two stories in height and provide a non-fire rated separation between the office space and the hangar bay. The north and south ends of the hangar bay consist of metal and glass horizontal sliding hangar doors. The roof consists of built-up tar and gravel over a corrugated metal deck. The roof slopes from a height of 14.9 m at the center of the hangar toward the east and west walls which are 13.4 m high. The metal deck is directly supported by 0.25 m I-beams which run the width of the hangar and are spaced 4.1 m on center. The I-beams are supported by open steel trusses which run perpendicular to the beams and are spaced 6.1 m on center. These trusses span the full length of the hangar. The roof also contains two skylights each of which measures 73.2 m long, 6.1 m wide, and 3.7 m high. The skylights are 36.6 m apart and run parallel to the hangar doors. Draft curtains were fabricated and installed in the 15 m facility to enclose an area 24.4 m x 18.3 m. The draft curtain was 3.7 m deep. In all experiments, the fire was located in the center of the draft curtained area as shown in figure 1.

A plan view of the hangar bay and fire area for the 22 m hangar is shown in figure 3. The hangar bay dimensions are approximately 73.8 m by 45.7 m. The hangar roof is barrel-shaped with a ceiling height ranging from 12.2 m at the bottom of the arch to 22.3 m directly over the center of the hangar. Corrugated steel draft curtains subdivide the ceiling into five equal bays approximately 14.8 m in width and 45.7 m in length. The draft curtains extend down to approximately 13.4 m above the floor.

MEASUREMENTS

Over 200 sampling points were continuously monitored during each of the 33 full-scale experiments. Measurements taken included plume and ceiling jet temperatures, smoke filling, radiation, ceiling jet

Table 1. Summary of Full-Scale Experiments.

Test Facility	Pan Size	Fuel	Conditions*	Test Duration
15 m	0.3 m x 0.3 m	JP-5		977 s
15 m	0.3 m x 0.3 m	JP-5	No Draft Curtain	681 s
15 m	0.6 m x 0.6 m	JP-5		727 s
15 m	0.6 m x 0.6 m	JP-5	No Draft Curtain	735 s
15 m	0.9 m x 0.9 m	JP-5		673 s
[illegible] m	1.5 m diameter	JP-5		578 s
[illegible] m	2.0 m diameter	JP-5		537 s
15 m	2.0 m diameter	JP-5	No Draft Curtain	744 s
15 m	2.0 m diameter	JP-5	No D.C./Open Doors	155 s
15 m	2.5 m diameter	JP-5		563 s
15 m	2.5 m diameter	JP-5	No Draft Curtain	517 s
22 m	0.3 m x 0.3 m	JP-5	2 Experiments	674 s/693 s
22 m	0.3 m x 0.3 m	JP-8		610 s
22 m	0.6 m x 0.6 m	JP-5	2 Experiments	620 s/638 s
22 m	0.6 m x 0.6 m	JP-8	2 Experiments	613 s/618 s
22 m	0.9 m x 0.9 m	JP-5	2 Experiments	619 s/621 s
22 m	0.9 m x 0.9 m	JP-8		621 s
22 m	1.2 m x 1.2 m	JP-5	2 Experiments	609 s/623 s
22 m	1.2 m x 1.2 m	JP-8		629 s
22 m	2.0 m diameter	JP-5		679 s
22 m	2.5 m diameter	JP-5		641 s
22 m	2.5 m diameter	JP-5	Open Doors	383 s
22 m	2.5 m diameter	JP-5	Open Doors	380 s
22 m	3.0 m x 3.0 m	JP-5	2 Experiments	659 s/665 s
22 m	3.0 m x 3.0 m	JP-8		668 s
22 m	4.6 m x 4.6 m	JP-5		294 s
22 m	4.6 m x 4.6 m	JP-5		424 s

* Each test was conducted with hangar doors closed and a draft curtain unless stated otherwise.

velocity, mass loss, and wind speed and direction. Measurements were taken using type K, chromel-alumel thermocouples; circular foil, water-cooled, Gardon-type heat flux radiometers; hot wire, temperature-compensated mass flow meters; load cells and anemometers.

Numerous fire detectors and sprinklers were installed and monitored. The type of fire detectors included combination infrared and ultraviolet optical flame detectors, spot-type photoelectric smoke detectors, spot-type heat detectors, line-type heat detectors and projected beam smoke detectors. The automatic sprinklers utilized were wired to determine activation time. The type and temperature of the sprinkler heads varied from 79 °C quick response heads to a 182 °C standard response head. Individual sprinkler heads were piped to simulate both wet-pipe and dry-pipe configurations. Sprinkler heads were not permitted to flow water during the experiments; only their activation times were recorded. In addition, each experiment was fully documented by the use of video cameras at various angles to the fire.

Locations of thermocouples, sprinklers, mass flow meters, and radiometers in the 15 m and 22 m facilities are shown in figures 2 and 4 respectively. Distances shown in figures 2 and 4 are in meters and represent either radial distance from the centerline of the fire or vertical distance below the ceiling. Spot-type thermal detectors were installed adjacent to the sprinkler locations shown in the diagrams.

RESULTS

Burn Rate, Heat Release Rate

The burn rates of JP-4, JP-5 and JP-8 were measured in a cone calorimeter. For each fuel, three experiments were conducted. The burn rates for JP-5 and JP-8 were 24 percent less than those measured for JP-4. The average burn rate for JP-5 was 7.0×10^{-3} kg/m²/s and for JP-8 was 6.9×10^{-3} kg/m²/s. The average burn rate for JP-4 was 9.3×10^{-3} kg/m²/s. Heat release rates averaged 330 kW/m², 320 kW/m², and 400 kW/m² for JP-5, JP-8, and JP-4 respectively.

Burn rates for the 1.0 m and 1.2 m diameter fires of JP-4, JP-5, and JP-8 conducted in the NIST large calorimeter are presented in the table 2. Multiple entries indicate experiments that were repeated. For all three fuels, the burn rates remained constant or decreased as the fire diameter increased from 1.0 m to 1.2 m. This indicates that the fire size has reached the point where radiation is the dominant heat transfer mechanism. Although burn rates vary based on transient effects, lip height, wind effects, and poor mixing at large pool diameters, after the point where radiation dominated burning is reached, the burn rate will remain relatively constant as fire size increases.

Table 2. Burn Rates (kg/m²/s) - Jet Fuel Fire Tests

Fuel Type	1.0 m diameter pan	1.2 m diameter pan
JP-4	0.076, 0.092, 0.114	0.0660
JP-5	0.063, 0.077	0.055, 0.067
JP-8	0.063, 0.093, 0.102	0.059, 0.060

Burn rates were measured in the full-scale experiments by use of a load cell platform. Burn rates reported are the steady state burn rates taken from the linear part of the mass loss curve. Heat release rates for the full-scale experiments were calculated from the measured burning rates by multiplying the burn rate by the associated heat of combustion of the respective fuel. Burn rates measured in the full-scale experiments were consistently lower than those measured in the laboratory scale experiments. One contributing factor may be that the pans in the full-scale tests were only half filled whereas the pans in the laboratory scale tests were completely filled. Burn rates and heat release rates from the full-scale experiments are presented in table 3. In the 2.5 m diameter fire in the 15 m high facility, mass loss data were not obtained due to a malfunction in the load cell. Burn rate data were, instead, estimated from the residual fuel measurement compared with the volume of fuel initially loaded into the fire pan. In this case, the burning rate reported is lower as the reported burn rate is not a steady state burn rate, it takes into account the growth phase of the fire. The heat release rate calculated for this fire using plume theory and measured plume centerline temperature at the ceiling is approximately 11 MW.

Maximum Ceiling Temperature

The maximum ceiling temperatures measured directly over the plume centerline, 0.15 m below the ceiling are presented in table 3. Multiple entries indicate repeat tests were conducted. Measured temperatures are compared to those calculated using plume theory. A radiative fraction of 35 percent was assumed[8,9]. Measured plume centerline temperatures at the ceiling show good agreement with those calculated from plume theory in all experiments in the 15 m high facility. In the 22 m high facility good agreement is shown for the smaller fires only.

Table 3. Burn Rates and Heat Release Rates - Full-Scale Experiments

Test Facility	Fuel Type	Pan Size (m)	Burn Rate $kg/m^2/s$	Heat Release Rate MW	Max Temp. (data) °C	Max Temp. (theory) °C
15 m	JP-5	0.3 x 0.3	0.025	0.1	30-34	31
15 m	JP-5	0.6 x 0.6	0.032	0.5	43-44	41
15 m	JP-5	0.9 x 0.9	0.055	1.9	56	60
15 m	JP-5	1.5 dia.	0.036	2.8	71	69
15 m	JP-5	2.0 dia.	0.050	6.8	105-112	106
15 m	JP-5	2.5 dia.	0.037[a]	7.7[a]	150-157	107[a]
22 m	JP-5	0.3 x 0.3	0.023	0.1	12-14	11
22 m	JP-5	0.6 x 0.6	0.045	0.7	21-23	18
22 m	JP-5	0.9 x 0.9	0.049-0.052	1.7-1.8	33-34	26
22 m	JP-5	1.2 x 1.2	0.042	2.6	48-49	30
22 m	JP-8	0.3 x 0.3	0.043	0.2	11	12
22 m	JP-8	0.6 x 0.6	0.039-0.057	0.6-0.9	17-18	19
22 m	JP-8	0.9 x 0.9	0.046	1.6	27	24
22 m	JP-8	1.2 x 1.2	0.042	2.6	40	30
22 m	JP-5	2.0 dia.	0.038	5.2	71	42
22 m	JP-5	2.5 dia.	0.038	7.9	93	53
22 m	JP-5	3.0 x 3.0	0.037-0.039	14.4-15.1	170-176	74
22 m	JP-8	3.0 x 3.0	0.034	13.3	175	70

[a] Heat release rate estimated by comparing input fuel to residual fuel.

Closed-head sprinkler systems versus deluge sprinklers:

The largest fire conducted in the 15 m facility was a 2.5 m diameter JP-5 pool fire. This fire was large enough to cause unacceptable damage to high value military aircraft, yet did not activate any of the 141°C sprinklers, even at plume center. These results bring the use 141 °C closed head sprinklers into question, and suggest that if closed head sprinklers are to be a viable alternative to open head deluge systems, the use of 79 °C quick response sprinklers should be considered.

Effect of draft curtains on sprinkler activations - 15 m facility:

Depending on fire size and temperature rating of the sprinkler heads, the draft curtains significantly affected either the number of sprinklers activated or the response time of the sprinklers. In the 2.0 m fire with the draft curtain, 17 sprinklers activated, while only 6 sprinklers activated in the 2.0 m diameter fire without the draft curtain. The 2.0 m diameter fire without the draft curtain activated the 79 °C standard and quick response sprinklers at fire center and the 79 °C quick response sprinklers 3.0 m from fire center. The 2.0 m diameter fire with the draft curtain activated all 79 °C quick response sprinkler heads 6.1 m or less from the fire center. In each of the 2.5 m diameter fires (i.e., both with and without the draft curtain), 18 sprinklers activated. However, sprinkler activation times outside the plume were approximately twice as long in the fire without the draft curtain compared to the fire with the draft curtain.

Effect of building height on sprinkler activation temperature rise:

As ceiling height increases, the fire size needed to activate ceiling-level fire protection devices also increases. The threshold fire size for sprinkler activation was a 2.0 m diameter pan fire in the 15 m hangar, and a 2.5 m diameter pan fire in the 22 m hangar. In the 15 m hangar, the 2.0 m diameter fire (with the draft curtain) effected an 84 °C temperature rise above ambient at the ceiling. This resulted in a maximum ceiling temperature of 112 °C which activated 16 of the 79 °C sprinklers and one 93 °C quick response sprinkler. By comparison, the 2.0 m diameter fire in the 22 m hangar effected a 61 °C temperature rise above ambient at the ceiling. This resulted in a maximum ceiling temperature of 71 °C which is below the activation temperature of the lowest rated sprinkler heads used in these experiments (i.e., 79 °C quick response).

In the 15 m hangar, the 2.5 m diameter fire (with the draft curtain) effected a 125 °C temperature rise above ambient at the ceiling. This resulted in a maximum ceiling temperature of 150 °C. By comparison, the 2.5 m diameter fire in the 22 m hangar caused an 82 °C temperature rise above ambient at the ceiling, and a maximum ceiling temperature of 93 °C.

Spacing of spot type heat detectors

Present U.S. fire codes require that spot-type heat detectors be installed at a reduction of their listed spacing for ceiling heights between 3.1 m and 9.1 m, and offer little or no guidance for ceiling heights in excess of 9.1 m[10]. The data collected in these experiments using rate-compensated heat detectors with both 57 °C and 93 °C activation temperature strongly suggest that a reduction in their listed spacing is not necessary for JP-5 and JP-8 fuel fires with ceiling heights ranging from 15 m to 22 m.

ONGOING/FUTURE WORK

The results of the projected beam smoke detectors, UV/IR flame detectors, spot-type photoelectric smoke detectors, line-type heat detectors and many of the other parameters investigated are not included in this brief paper. The relationship between the aviation fuel type and the detector response has not been fully quantified; however, preliminary analysis does not indicate a significant difference in the selection and placement of detection devices. Full documentation of the test procedures, data analysis, conclusions, and a professional video will be available with the publication of the NIST technical report.

The results of this project will be used in reevaluating fire protection design criteria for all military aircraft hangars. It is anticipated that these data will also be used in evaluating fire protection criteria for commercial aircraft hangars as well.

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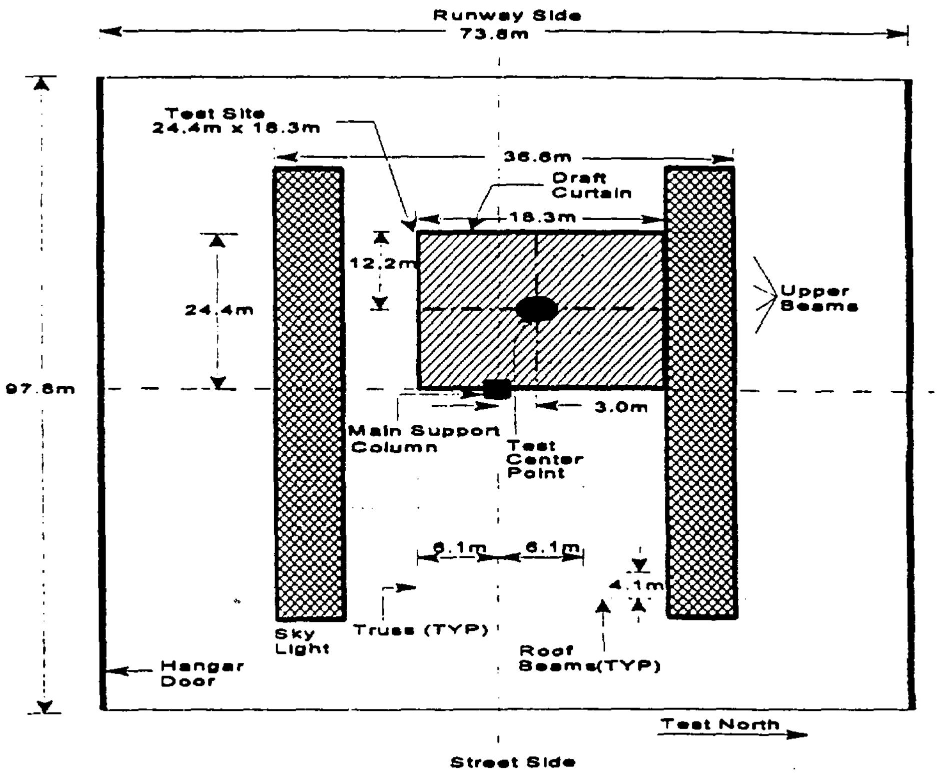

Figure 1. Plan view of hangar bay, 15 m facility.

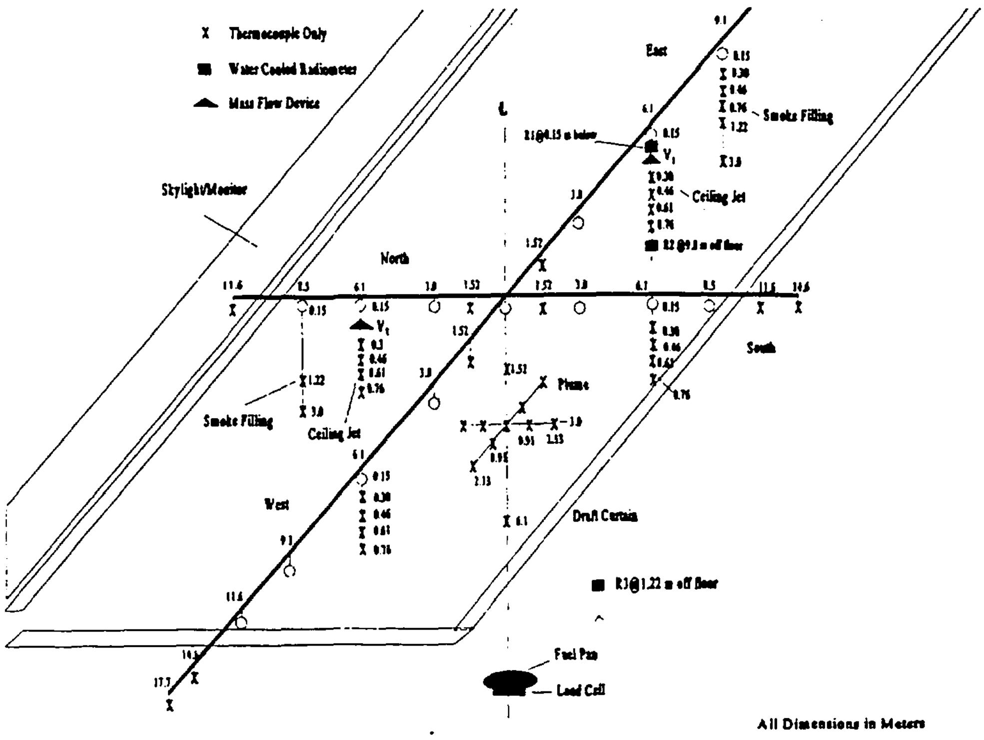

Figure 2. Instrumentation locations in 15 m high facility.

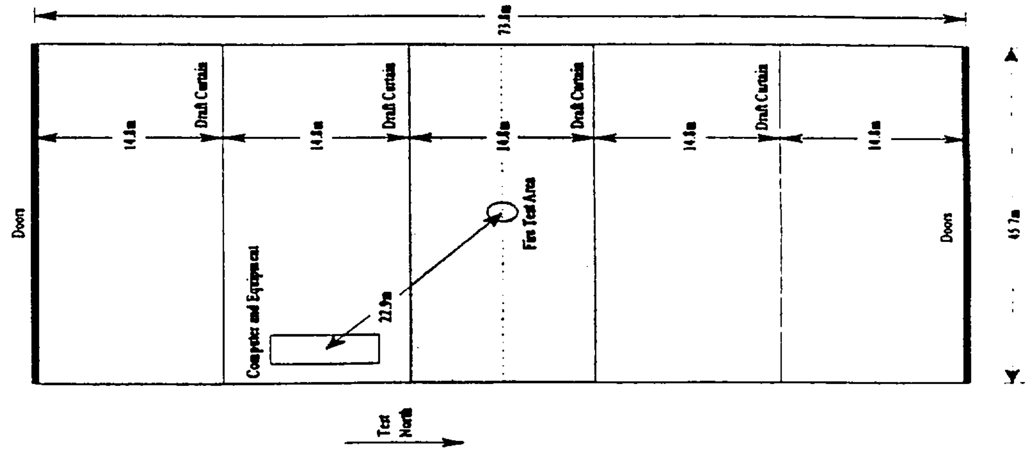

Figure 3. Plan view of hangar bay, 22 m facility.

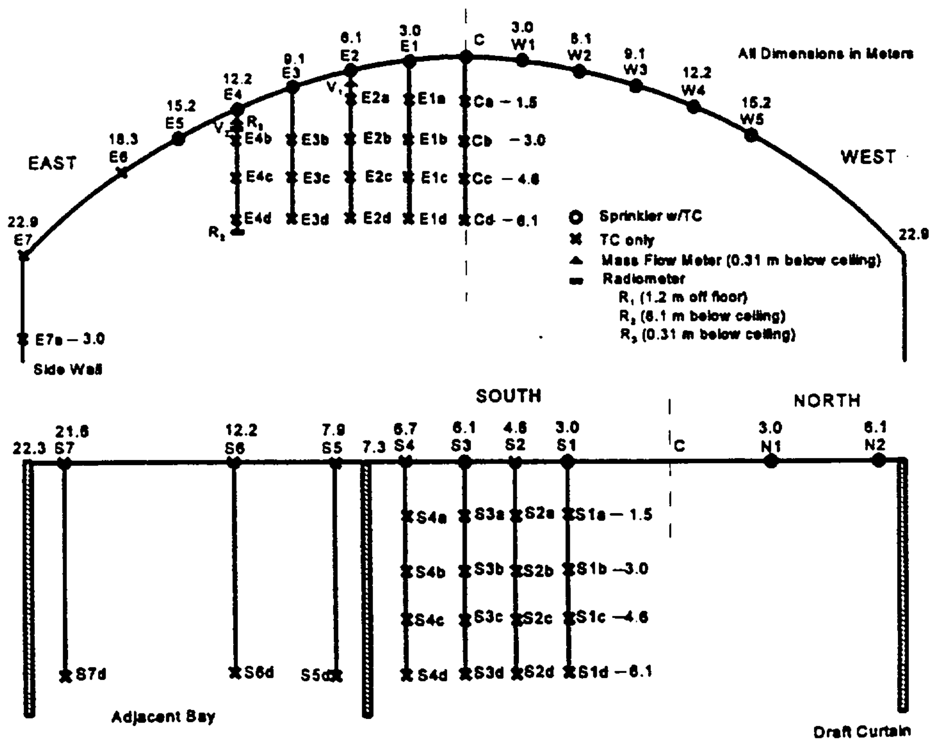

Figure 4. Instrumentation locations in 22 m high facility.